Blockchain in the built environment and construction industry: A systematic review, conceptual models and practical use cases

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Highlights

- Identifies recent challenges facing the construction industry and recognises current attempts of exploring distributed ledger technology (DTL) as part of the solution to some of these challenges.
- Performs a systematic review of DLT uses in the built environment and construction industry and identifies seven distinct areas of applications.
- Introduces an extended socio-technical framework for implementation of DLT into the construction industry including two conceptual models: the DLT Four-Dimensional Model, and the DLT Actors Model.
- Compiles an extensive list of challenges and opportunities presented by DLT across the four dimensions (technical, process, policy, social) to offer a state-of-the-art review of its current state.
- Presents a decision support tool to appraise the suitability of use cases for DLT applications and demonstrates it with three use cases.

Abstract

The construction industry is facing many challenges including low productivity, poor regulation and compliance, lack of adequate collaboration and information sharing, and poor payment practices. Advances in distributed ledger technologies (DLT), also referred to as Blockchain, are increasingly investigated as one of the constituents in the digital transformation of the construction industry and its response to these challenges.

The overarching aim of this study was to analyse the current state of DLT in the built environment and the construction sector with a view to developing a coherent approach to support its adoption specifically in the construction industry. Three objectives were established to achieve this: (a) to present the first state-of-the-art and literature review on DLT in the built environment and construction industry providing a consolidated view of the applications explored and potential use cases that could support disruption of the construction industry. Seven use-categories were identified: [1] Smart Energy, [2] Smart Cities & the Sharing Economy, [3] Smart Government, [4] Smart Homes, [5] Intelligent Transport, [6] BIM and Construction Management, and [7] Business Models and Organisational Structures; (b) to propose a framework for implementation composed of two conceptual models (i.e. DLT Four-Dimensional Model, and the DLT Actors Model), developed according to extended socio-technical systems theory and including four dimensions (technical, social, process and policy), to support the development of DLT-based solutions that are adequate to the challenges faced by the construction industry. The DLT Four-Dimensional Model and the DLT Actors Model contribute to improve the understanding of the concepts involved when discussing DLT applications in construction and represent flexible, adaptable and scalable knowledge constructs and foundations that can be used for various further investigations; and (c) to appraise three specific use cases (i.e. Project Bank Accounts, regulation and compliance, and a single shared-access BIM model) as potential areas for DLT technologies through the application of a decision support tool. The results shows that Project Bank Accounts (PBAs) and regulation and compliance are candidate areas for DLT applications and warrant further attention. However, for the third use case (i.e., single shared-access BIM model) DLT technologies are still insufficiently developed at this time.

The research shows that there is real potential for DLT technologies to support digitalisation in the construction industry and enable solutions to many of its challenges. However, there needs to be further investigation of the readiness of the industry, its organisations and processes, and to evaluate what changes need to occur before implementation can be successful. Further investigations will include the development of *readiness metrics* for the four dimensions to evaluate readiness levels within a series of use cases for the construction industry.

Keywords: blockchain technologies; distributed ledger technology (DLT); socio-technical systems; use cases; Project Bank Accounts (PBAs); regulations and compliance; built environment; construction industry.

1 Introduction

Globally, construction spending is projected to reach US$12.4 trillion by 2022 (PR Newswire, 2018). In the United Kingdom (UK) alone an estimated £600bn will be spent over the next 10 years on public and private infrastructure resulting in efficiency and productivity improvements in the delivery of construction projects becoming strategic priorities for the UK Government (Neely, 2018). Currently, poor productivity is cited as a key aspect of failure in the construction industry (Farmer, 2016). Conversely, it is one of the biggest areas for potential improvement with McKinsey Global Institute (2017) reporting a global productivity gap of $1.6tr that can be tackled by improving the performance of the industry. The industry is perceived as slow to innovate, particularly in its adoption of digital technology (Agarwal *et al.*, 2016). There is some evidence of change, for example, through the advent of Building Information Modelling (BIM) (Succar and Kassem, 2015; Heiskanen, 2017; Mathews *et al.*, 2017) though global BIM adoption has been slow due to perceived risks and challenges at this stage of the technology's development and its supporting processes and standards (Ghaffarianhoseini *et al.*, 2017; Kinnaird and Geipel, 2018). There are also limitations in knowledge and understanding of BIM (Winfield and Rock, 2018) resulting in organisations' and individuals' misconceptions of what the technology can achieve; this often leads to abandonment and disappointment from those engaging with it (Panuwatwanich and Peansupap, 2013; Mathews *et al.*, 2017).

One of the main issues hindering the modernisation of the construction industry is its inability to embrace technological advancements in comparison with successes seen in logistics, automotive and mechanical engineering industries (Merschbrock, 2012; Cardeira, 2015; Oesterreich and Teuteberg, 2016; Barima, 2017; Mason, 2017). "*Blockchain*", or distributed ledger technology (DLT), is regarded as having the potential to transform many global industries including construction. Blockchain was developed as the underpinning technology for the world's first cryptocurrency, Bitcoin, introduced in 2008 as a verification tool for its transactions (Rasoloharijaona *et al.*, 2003). The term *"blockchain"* has now become synonymous with the concept of DLT and is used interchangeably. The generic term *distributed ledger technologies* (DLT) is adopted throughout this paper and includes, but is not limited to, the Bitcoin Blockchain.

For any technological advancement to become a viable and accepted solution in the construction industry, it must address the key challenges affecting through effective resolution of the underlying systemic cause(s). The key challenges affecting the construction sector have been highlighted in a number of recent reports and academic literature, which are summarised here to provide a baseline on which to consider throughout this paper and as a scene-setter for some of the problems DLT have the potential to help solve.

A review of the UK construction industry by Farmer (2016) identified 10 symptoms of failure and poor performance: low productivity; low predictability; structural fragmentation; leadership fragmentation; low margins, adversarial pricing models and financial fragility; a dysfunctional training, funding and delivery model; workforce size and demographics; lack of collaboration and improvement culture; lack of R&D and investment in innovation; and poor industry image.

Woodhead *et al.*, (2018) discuss the UK government's biggest challenges to construction as: austerity affecting the ability to secure funding for major projects; lack of affordable housing (making house building the biggest area of potential growth); an aging workforce without suitable succession planning; and the UK's exit from the European Union causing projects to be stalled or cancelled due to uncertainty and the potential loss of workforce as a result of changes to immigration. Woodhead *et al.,* (2018) identify three contradictions in relation to these challenges: the requirement to build more for less; deliver more without the available skills; and increase capital expenditure through increasing private sector investment in an environment of uncertainty which makes quantifying return on investment difficult.

In Dame Judith Hackitt's Independent Review of Building Regulations and Fire Safety (Hackitt, 2018) following the events of the Grenfell Tower fire in 2017, four key issues were highlighted as the underlying reasons for system failure: *ignorance* – regulations and guidance are not read by those required to comply with them or are misunderstood and/or misinterpreted; *indifference* – cutting costs and doing things as quickly as possible are drivers rather than providing safe, quality homes for residents; *lack of clarity on roles and responsibilities* – ambiguity over responsibilities and fragmentation across the industry result in preclusion of ownership and accountability; and *inadequate regulatory oversight and enforcement tools* – enforcement is often lacking and not informed by size or complexity of the project and penalties are insufficient to be an effective deterrent.

McKinsey Global Institute (2017) reports a productivity gap of $1.6 trillion a year in global construction. To benefit from this gap the industry only needs to make efficiencies with digitalisation being cited as the best driver for change. However, construction companies tend to underinvest in IT and technology and neglect research and development activities. Improvements and changes in regulation can facilitate industry shifts as seen in Australia, Germany and Singapore where positive impacts are being seen through streamlining processes, clamping down on corruption through promoting transparency, investing in R&D, creating more standardised building codes and putting the focus on project outcomes.

Finally, payments are one of the construction industry's biggest problems with regards contractual entitlements being paid late, not being paid at all or being held up as a result of disputes which can often result in business failure (Cardeira, 2015; Wang *et al.*, 2017b).

The overarching aim of this study was to analyse the current state of DLT in the built environment and the construction sector on which to support development of a coherent roadmap for their adoption in the construction industry. Three objectives were established to achieve this: (1) to present the first state-of-the-art and literature review on DLT in the built environment and construction industry providing a consolidated view of the applications explored and potential use cases that could support disruption of the construction industry; (2) to propose a framework for implementation composed of two conceptual models based on extended socio-technical systems theory and data obtained from a systematic literature review; and (3) to appraise three specific use cases (i.e., Project Bank Accounts, regulation and compliance, and a single shared-access BIM model) as potential areas for DLT through the application of a decision support tool. Section 2 defines DLT and its related concepts. Section 3 addresses objective (1) presenting the methodology adopted for this paper and provides the results from three research sieves: a systematic literature review of the-state-of-the-art of DLT in the built environment, a focus group and expert interview that were used to develop the conceptual models. Assimilating the knowledge described in Section 3, Section 4 proposes two conceptual models, the DLT Four-Dimensional Model and the DLT Actors Model, developed in accordance with the extended socio-technical framework to satisfy objective (2). Section 5 focuses on objective (3) by presenting a decision support tool for analysing the suitability of use cases for DLT applications and tests three of the use cases identified using the tool. Finally, Section 6 concludes the paper and offers suggestions for further work.

2 Key terms and concepts

Blockchain and distributed ledger technology (DLT)

Distributed ledger technology (DLT), also referred to as *blockchain*, is regularly represented as having the transformative power to change everything from the way commerce operates to driving the economy on a global scale (Tapscott and Tapscott, 2016). In the remainder of the paper, the term DLT is generally adopted except when reviewing working by other authors who had used the 'blockchain' term. There are key advantages in its inherent immutability, transparency and the way it redefines the trust relationship by offering solutions that are fast and secure and can operate publicly or privately (Underwood, 2016). O'Boyle (2017) has characterised blockchain as an 'internet of value', and its impact over the next 10 to 20 years could match that of the internet due to its decentralisation and irrevocable nature (Khaqqi *et al.*, 2018). It has the potential to change the way applications are developed, create efficiencies and drive digital transformation in many, perhaps all, industries including the construction industry (Mathews *et al.*, 2017).

The key features of DLT (here characterised by the Bitcoin Blockchain) are: (i) decentralisation operating across a peer-to-peer network made up of computers (known as *nodes*); (ii) immutability, once blocks are chained; (iii) reliability, given that all nodes have an identical copy of the blockchain which is checked through an algorithm and highlights any anomalies; (iv) authentication: in the Bitcoin blockchain, a Proof-of-Work mechanism is used to validate transactions and uses a mathematical and deterministic currency issuance mechanism to reward its miners (Kypriotaki *et al.*, 2015; Swan, 2016; Turk and Klinc, 2017). The miner completing the mathematical equation first wins the right to mine the block to the blockchain and in return for their efforts, is rewarded in Bitcoin (Dorri et al., 2017b). Its design ensures security and uses cryptography and a distributed consensus mechanism, which offers anonymity, persistence, auditability, resilience and fault tolerance (Hamida *et al.*, 2017).

When a transaction is broadcast to the network, it is received by all nodes who validate and verify its existence though running pre-defined checks regarding the structure and activity within the transaction (Karafiloski and Mishev, 2017). Blocks are considered valid when a majority of the nodes (51% or more) reach a consensus (Biswas and Muthukkumarasamy, 2016). Upon mining the block to the blockchain each node's version of the blockchain is updated. It should be noted that the blockchain itself is simply a distributed ledger; it does not have the ability to perform computations, these are done outside of the blockchain by miners who then mine blocks of verified and validated transactions to the blockchain (Mik, 2017). In public blockchains it is near-impossible to change a block due to visibility across the network (Tapscott and Tapscott, 2016) and to the fact that it must be changed along with all blocks succeeding it in the time it takes to mine just one block to the blockchain (Yermack, 2017). In addition, all blocks link back to the genesis block ensuring the blockchain's integrity (Nofer *et al.*, 2017). In private blockchains, changes are simply made when all nodes agree that it can be changed by consensus, typically off-line, following which the data is modified. Access rights in private blockchains make data privacy stronger (Hamida *et al.*, 2017).

Perhaps one of the most important aspects of DLT for construction is smart contracts. They are self-executing pieces of code that execute the terms of a contract (Szabo, 1994) upon pre-set obligations being met (Boucher *et al.*, 2017). Smart contracts can also be considered as *automatable* traditional contracts as there are elements that may still require human input and control (Clack *et al.*, 2016). In very simple terms, smart contracts are made up of *if/then* commands and reduce the need for intermediaries, minimise the amount of physical paperwork (Cohn *et al.*, 2017), and can contribute to reduce possible attacks and fraud, arbitration and enforcement costs (Tapscott and Tapscott, 2016). According to the Winfield-Rock Report, blockchain coupled with smart contracts can solve some of the problems of BIM adoption including increasing trust and collaboration as "[t]he availability of a real-time, change-resistant and hack-resistant record of data with trustworthy time entries increases the reliability, integrity and transparency of the data" (Winfield and Rock, 2018, p. 39). The report also notes that there remain many aspects to be addressed such as untested legal issues as well as the continuing need for clear and express contract terms and mitigating measures that reduce the risk that parties take on unintended obligations and disputes (Winfield and Rock, 2018).

One of the challenges presented for longer-term contracts is transaction longevity: where a contract is coded today for execution in many years (e.g. wills or futures), particularly when external information sources may no longer exist (Mason, 2017). The complexity of coding smart contracts and the requirement for them to be coded correctly, given that they will be forever sitting in a public ledger, may limit or delay their adoption and acceptance within the mainstream (Frantz and Nowostawski, 2016). It is suggested by Boucher *et al.,* (2017) that, due to the initial set up costs and requirement of effort, they are currently better suited to repetitive agreements rather than one off contracts or contracts with a long duration that are often subject to variations. Other barriers to full implementation of smart contracts are concerned with storage constraints, interoperability, reliability of the data input and confidentiality (Mason, 2017).

3 Research Methodology

This section describes the process taken to perform the systematic literature review and provides a description of the results obtained from it including the extensive list of challenges and opportunities compiled from the literature that informed development of the framework and bibliometric indicators that describe the body of literature reviewed. In addition, the remaining research methods used to develop the framework are explained, namely, a focus group discussion, an in-depth interview and the socio-technical systems approach adopted.

3.1 Results of a Systematic Literature Review

A systematic literature review (SLR) was conducted to: identify the current applications of DLT in the built environment; to evaluate the extent to which DLT is addressed as a socio-technical system in the current body of research; and to determine the key challenges and opportunities facing DLT applications in the built environment. The construction industry creates, adapts and supports evolution of the built environment, all aspects of which (energy, infrastructure, transport, built assets etc.) impact on what is constructed (or renovated) and how new built assets integrate in the ecosystem around it. Therefore, the scope of this literature review extends to the built environment providing a coherent understanding of what DLT can do for construction and its interactions with the built environment. Moreover, as the literature shows, applications such as smart energy and smart government are at a more developed stage of DLT implementation than the construction industry thus, it is important to scholars with an interested in construction to unravel such applications.

The results of the SLR informed the development of an extended socio-technical framework summarising the challenges and opportunities from multiple dimensions (technical, policy, process and social). From searches in three databases (Scopus, ScienceDirect and Web of Science) 534 papers were returned. After removal of duplicates, application of inclusion and exclusion criteria and review of abstracts, 32 papers were selected for review. Further searches were conducted in Google Scholar following a more traditional route and an additional 41 papers were added over a period of around 6 months, resulting in 73 papers being reviewed in total. Following initial content analysis of these papers the applications of DLT in the built environment were grouped into seven categories as detailed in Table 1. Papers concerning the technological architecture of DLT were not included in this review. Moreover, additional papers concerning smart energy were not included beyond the first three databases given the extensive real-world application and development of DLT in the energy industry; it was felt this area was sufficiently covered by the initial search for this review and further analysis of the category would detract from the core aims of this study.

Table 1: Categories of DLT applications in the built environment

Category	No. of papers	References
[1] Smart Energy	22	(Mihaylov *et al.*, 2014; Murkin *et al.*, 2016; Kianmajd *et al.*, 2016; Castellanos *et al.*, 2017; Di Silvestre *et al.*, 2017; Mylrea and Gourisetti, 2017; Nehaï and Guerard, 2017; Rottondi and Verticale, 2017; Sikorski *et al.*, 2017; Hahn *et al.*, 2017; Tanaka *et al.*, 2017; Wang *et al.*, 2017a; Hwang *et al.*, 2017; Imbault *et al.*, 2017; Kang *et al.*, 2017; Kounelis *et al.*, 2017; Mengelkamp *et al.*, 2018b; Park *et al.*, 2018; Pieroni *et al.*, 2018; Pop *et al.*, 2018; Khaqqi *et al.*, 2018; Mengelkamp *et al.*, 2018a)
[2] Smart Cities & the Sharing Economy	7	(Biswas and Muthukkumarasamy, 2016; Huckle *et al.*, 2016; Sun *et al.*, 2016; Ibba *et al.*, 2017; Pazaitis *et al.*, 2017; Rivera *et al.*, 2017; Swan, 2018)
[3] Smart Government	12	(Atzori, 2015; Ølnes *et al.*, 2017; Sullivan and Burger, 2017; Boucher *et al.*, 2017; Hanifatunnisa and Rahardjo, 2017; Hou, 2017; Kovic, 2017; Maupin, 2017; Nordrum, 2017; Alketbi *et al.*, 2018; Engin and Treleaven, 2018; Jun, 2018)
[4] Smart Homes	4	(Dorri *et al.*, 2017a, 2017b; Lazaroiu and Roscia, 2017; Zhu *et al.*, 2017)
[5] Intelligent Transport	12	(Yuan and Wang, 2016; Yang *et al.*, 2017; Dorri *et al.*, 2017c; Hou *et al.*, 2017; Kang *et al.*, 2017; Kim *et al.*, 2017; Sharma *et al.*, 2017; Cebe *et al.*, 2018; Decoster and Billard, 2018; Knirsch *et al.*, 2018; Pedrosa and Pau, 2018; Strugar *et al.*, 2018)
[6] Building Information Modelling (BIM) & Construction Management	11	(Barima, 2017; Belle, 2017; Heiskanen, 2017; Mason, 2017; Mathews *et al.*, 2017; Turk and Klinc, 2017; Wang *et al.*, 2017b; Ye *et al.*, 2018; Kinnaird and Geipel, 2018; Mason and Escott, 2018; McNamara and Sepasgozar, 2018)
[7] Business Models & Organisational Structures	7	(Kypriotaki *et al.*, 2015; Boucher *et al.*, 2017; Hossain, 2017; Nowiński and Kozma, 2017; Tapscott and Tapscott, 2017; Zhang and Wen, 2017; Johng *et al.*, 2018)

3.1.1 DLT applications in the built environment

This section provides a succinct summary of the emerging applications of DLT in the built environment using the seven categories illustrated above.

[1] Smart Energy

Until recently, energy has been traded by Major Power Producers (MPPs) who have led the market and set prices; they still make up 94% of the electricity production market (Murkin *et al.*, 2016). However, due to the falling cost of renewable technologies and the increase in prosumer-behaviour (European Parliament, 2016) this market is opening up to offer more opportunities to individual, residential producers of electricity, primarily those who use solar photovoltaic panels on their home and who produce an excess to that which they need to run their home, to sell it to the grid or to their neighbours. Currently, trades are done via MPPs, however, microgrids managed through DLT are making this possible in a decentralised way directly from prosumer to consumer (Castellanos *et al.*, 2017).

Internet of Things (IoT) devices coupled with smart contracts running on DLT are reducing congestion and faults related to distribution and demand management is being revolutionised through monitoring using sensor technologies (Mylrea and Gourisetti, 2017; Pieroni *et al.*, 2018; Pop *et al.*, 2018) that regulate power usage automatically through smart contracts and/or inform homeowners of their usage allowing them to make sustainable changes to their energy consumption and lifestyle choices (Hwang *et al.*, 2017; Imbault *et al.*, 2017).

Automated auction mechanisms running on DLT allow multiple buyers and sellers to purchase energy from one another and are transforming the way in which users purchase energy becoming more passive through automation (Hahn *et al.*, 2017; Tanaka *et al.*, 2017; Wang *et al.*, 2017a; Mengelkamp *et al.*, 2018b). Through this, individuals and/or communities become more independent from the grid through microgeneration, which benefits the environment and allows prosumers to generate better profits based on demand and supply (Murkin *et al.*, 2016). Energy efficiency is key to achieving many of the "smart" goals such as smart city, smart home and smart government as so much relies on the ability to manage energy usage and ensure supply (Park *et al.*, 2018). The construction industry must account for this in its designs for new built assets and where existing assets are renovated and/or repaired. The key challenges cited in these papers relate to lack of regulation and nascence of DLT.

[2] Smart Cities and the Sharing Economy

A smart city is the integration of resources where human and social capital interact using technological solutions (Pieroni *et al.*, 2018). The concept is a response to projected increases in urban migration (Sharma *et al.*, 2017) putting immense pressures on the built environment to manage this increase. Advances in information and communication technology (ICT) and the IoT have made the sharing economy much easier and more accessible (Huckle *et al.*, 2016; Pazaitis *et al.*, 2017) allowing people to see real-time data about the availability of resources to make better-informed choices. It is a social model that helps power the economy led by supply and demand. It can lead to further innovation, growth and employment, opening up new social and ecological opportunities. Value is created collaboratively, channelled through financial markets and is decentralised but controlled centrally by organisations (e.g. Facebook and Airbnb) who determine how rewards are distributed via dividends, wages, rents etc. (Pazaitis *et al.*, 2017). However, there is a requirement for robust governance to protect users, particularly regarding unskilled providers, fraud and liability (Sun *et al.*, 2016).

Ibba *et al* (2017) introduce the use of smart devices, the IoT and blockchain to monitor and control air quality through a city. DLT-based distributed applications (dApps) and Decentralised Autonomous Organisations (DAOs) allow people to monetise their items when idle or not at full capacity (e.g. car sharing and ride sharing) (Huckle *et al.*, 2016; Sun *et al.*, 2016). DLT allow communications between entities to be more private and secure (Biswas and Muthukkumarasamy, 2016). Further DLT use cases include: near real-time payments across borders; monitoring of population growth; maintenance of health records and granting access to relevant parties; more fair and democratic elections through improved participation; and improving government operations through reduction of bureaucracy and increased efficiency. Individuals have greater control over their own personal data making it easier for them to prove their identity and share it when and how they see fit. Estonia is the first country to have a blockchain-based identity system where chipped identity cards hold personal data along with two certificates that authenticate a person's identity and provide a digital signature. The same ID card can be used to purchase tickets for public transport and order and collect prescriptions from a pharmacy (Rivera *et al.*, 2017)

There is a shift of emphasis from price to value giving communities the ability to create proprietary value systems on DLT based on what they deem important, a basis for which sharing of resources and services is at the centre and puts the community in control of creating business logic and productive processes (Pazaitis *et al.*, 2017). Emphasis is placed on mutual benefit to suppliers of data (e.g. citizens) and collectors of data (e.g. government) encouraging citizens to engage in the smart city (Ibba *et al.*, 2017). Collaboration of technology, humans and organisations sits at the centre of this environment (Sun *et al.*, 2016). The IoT, coupled with DLT, makes the system more secure and ubiquitous. Swan (Swan, 2018) discusses the citizen taking back control of themselves and their societies through creation of a "*Cryptopolis*" and a more trusting society built on DLT incorporating "economic self-definition, the civic responsibility of the cryptocitizen, a social theory of dignity for mutual coexistence, and the future of work (meaning the ability to meet higher-level Maslow needs in the automation economy) (Swan, 2018). However, issues remain where automation of tasks is involved, particularly regarding which activities to automate and which should remain under human control (Pazaitis *et al.*, 2017).

[3] Smart Government

DLT are being investigated, trialled and employed across many governments globally including in the United Arab Emirates, the United States (Nordrum, 2017), Sweden, Ukraine, United Kingdom (Jun, 2018), Denmark, Honduras (Alketbi *et al.*, 2018), the Republic of Georgia (Engin and Treleaven, 2018) and Estonia (Sullivan and Burger, 2017) . Jun (2018) provides a comprehensive list of 17 nations and some of their blockchain-based government projects in addition to suggesting principles for their implementation as: Blockchain Statute law; disclosure of data and source code; implementing autonomous executing administration; building a governance system based on direct democracy; and making Distributed Autonomous Government (DAG). Other applications in this category focuses on smart contracts to automate processes and public services including tax collection, identity management, benefits distribution, property and land registries, local and/or national digital currencies, government records management (Boucher *et al.*, 2017), regulatory compliance (Engin and Treleaven, 2018) and health care services (Alketbi *et al.*, 2018). Transparency and immutability offer accountability, efficiencies and reduced bureaucracy as a result of automation (Nordrum, 2017). In China, DLT is being explored to authenticate reliability of individuals' data allowing it to be used for an enterprise credit system providing mutual information exchange between individuals and enterprises helping each to make better informed decisions (Hou, 2017). Blockchain-based e-voting is discussed to reduce time and cost associated with electoral voting and making it more accessible to voters in remote areas bringing services to people rather than them having to physically go to a polling station (Kovic, 2017). An e-voting model based on blockchain to reduce fraud associated with manipulation of traditional databases was proposed by Hanifunnisa and Rahardjo (2017).

Atzori (2015) highlights a number of challenges associated with decentralisation of governance where power shifts over time from central bodies to groups of unknown people/code developers with unaccountable power resulting in a change of politics to electronic service delivery. There is potential for the rising of an anarchist state (Atzori, 2015) threatening to disrupt the international economic order (Maupin, 2017). Additional challenges to blockchain-based e-government services include costs of development implementation, nascence of the technology, long-term preservation of records, social memory and historical evidence. Several solutions are proposed including standardised technology to combat interoperability issues and implementation costs; collaboration between software developers and institutions from the outset; clarification of governance around blockchain and building robust security and privacy into the system ensuring longevity (Hou, 2017).

[4] Smart Homes

Smart homes, while covered only briefly in the literature, are likely to become archetypal for new builds and existing homes as devices and appliances are replaced with smart versions and conversions are made to existing homes. In Dorri *et al.,* (2017a) Blockchain is used to monitor and reduce energy consumption. Blockchain provides increased privacy and security in the smart home and despite increases in overhead due to use of low-resource IoT devices the benefits are deemed worthwhile (Dorri *et al.*, 2017b). Digital signatures can be used to identify suspicious activity while, at the same time, giving each smart home device its own identity. Monitoring systems complement the smart home by learning normal behaviour and then acting appropriately when non-normal behaviour is detected. Users are able to monitor and control conditions in their homes remotely such as temperature, distance, illumination, humidity, current, motion etc. (Zhu *et al.*, 2017). Lazariou and Roscia (2017) consider a residential smart district that allows people to remotely control their home but offers additional services such as educational development and recreation providing a smart playground where children generate electricity by playing on, for example, swings and slides; mobile charging stations placed by park benches and interactive tables in the bar for reading the news, playing games, watching television etc.; smart parking; a smart card payment system; smart swimming pool; bike sharing; and car sharing. Blockchain offers integration with the IoT and manages transactions within the smart district (e.g. giving users autonomy to produce, buy and sell energy from their home). Interoperability is cited as a challenge to smart home implementation given different manufacturers' reluctance to collaborate and communicate with other devices.

[5] Intelligent Transport

DLT is broadening possible applications within intelligent transport through integration with other applications such as smart energy and better use of resources (Kang *et al.*, 2017). Smart vehicles now have on-board storage for private data which, via the blockchain, owners can choose whether to grant access to third parties giving them more control over their data. Blockchain reduces security and privacy issues through encryption and authentication. Various applications are offered: remote software updates during manufacturing and for vehicle maintenance; flexible insurance based on data provided on driver behaviour (i.e. speed, braking habits etc.); smart vehicle charging which integrates with smart home, calendars, individual behaviours etc. for example, charging at times when electricity is cheapest; and enabling car sharing services when a vehicle is not in use by its owner where the blockchain facilitates the financial transaction, unlocking of the car, authorised access etc. (Dorri *et al.*, 2017c; Cebe *et al.*, 2018).

Mobile billing systems allow electric vehicle owners to charge their vehicles away from home via a blockchain-based payment system (Kim *et al.*, 2017). Leasing of private charging piles is facilitated by blockchain and smart leasing contracts removing third party intermediaries and ensure data privacy of transactions (Hou *et al.*, 2017). Sharma *et al.,* (2017) developed a system that integrates with public services such as the Department of Motor Vehicles for monitoring and management of traffic through a smart city. Blockchain is used for crowdsourcing of data incorporating smart contracts and eliminating the need for intermediaries. A seven-layer framework is applied to successful ride-sharing application, La'zooz, a self-managed DAO that rewards users who share their data during journeys with "zooz" tokens that can be used to pay for future journeys. The more people that allow their data to be crowdsourced in this way improves social performance of the service (Yuan and Wang, 2016). A reputation-based system is offered by Yang *et al.,* (2017) that crowdsources data about traffic conditions throughout a city. Decoster and Billard (2018) propose the use of intelligent cars to determine the best route through a city to avoid traffic delays without the use of a central internet service such as Google Maps or Tom Tom thereby preventing collection and storage of private data by a central organisation. In Knirsch *et al*., (2018), a dynamic four-step bidding system involving exploration of charging rates and locations, bidding, evaluation and charging is built on blockchain which allows users to choose from different options based on price and circumstances. Charging is done by setting a pre-agreed amount of tokens in Pedrosa and Pau (2018). Finally, Strugar *et al*., (2018) use the IOTA distributed ledger for facilitating billing, electric vehicle charging and machine-to-machine communication. Many of these developments are relevant to the construction industry and in particular, to the operation (in-use) phase of assets.

[6] Building Information Modelling (BIM) and Construction Management

The adoption of Building Information Modelling (BIM) has been commonly seen as a progression that involves levels of increasing capability maturity across technology, process and policy fields (Succar, 2009). Although it is generally accepted that BIM can benefit from integration with DLT there is a consensus that the degree of collaboration enabled by Level 2 BIM is insufficient and needs to advance into more networked and integrated forms such as those envisioned in Level 3 before this can be realised (Heiskanen, 2017; Mason, 2017; Kinnaird and Geipel, 2018). Level 2 BIM is a collaborative way of working, in which 3D models with the required data are created in separate discipline models according to a set of guides, standards and specifications (Kassem *et al.*, 2016). Level 3 BIM, also referred to as iBIM (integrated BIM), pertains to 'fully open' process and data integration enabled by web services; compliant with the Industry Foundation Classes (IFC) and buildingSMART Data Dictionary (bsDD) standards (BIM Dictionary, 2018). Level 3 BIM also focuses on working with a new contractual framework that promotes consistency, clarity, openness and collaboration in a culture that is cooperative and dedicated to learning and sharing (NBS, 2014). The integration of BIM, DLT, smart contracts and the IoT can have a significant impact on construction activities and facilities management, especially where tracking of components proves useful and where there is duplication of work; IoT tracking devices will automatically collect data regarding an item or a process and update the DLT accordingly (Heiskanen, 2017). DLT can be a solution to many issues that have slowed the adoption of BIM such as limited collaboration and information sharing. Where there are legal issues, and in the event of a single [shared-access] BIM model, ownership and rights (e.g. responsibilities, liabilities and intellectual property rights) can be made explicit and transparent to all project parties on the DLT leading to increased trust (Kinnaird and Geipel, 2018).

Issues of transparency and trust are highlighted by the World Bank in its overview of the key advantages of DLT/blockchain-enabled networks (World Bank Group, 2017). The issue of trust is an interesting one. On one hand the technology could remove or reduce the transaction costs traditionally associated with construction projects (Li *et al.*, 2015) in the drafting, negotiating and enforcing of agreements, thus, resulting in massive cost reductions and efficiency gains. On the other hand, such an outcome, if widespread, would have a truly disruptive effect on businesses, many of whom rely financially on the *status quo* of opportunism and contractual behaviour (Love *et al.*, 2010).

BIM is described by Mason (2017, p. 2) as a pre-cursor to intelligent contracts where DLT provides a platform for them to operate and where the two should be "viewed as part of the BIM-led revolution in construction and not separate from it". Semi-automation is the suggested approach rather than full automation due to limitations in the technology and BIM along with the need for human intervention in construction projects (Mason and Escott, 2018). Intelligent contracts running on a DLT can lead to surety of payments stabilising smaller contractors and increase trust in projects through the historical immutable record of a distributed ledger (McNamara and Sepasgozar, 2018).

Strengthening procurement and supply chain activities using smart contracts resulting in automated payments, provenance tracking, contract administration, disintermediation, ownership and control of data and redefining trust is offered by many authors (e.g. Barima, 2017; Mathews *et al.*, 2017; Zheng *et al.*, 2017). With regards facilities management, Kinnaird and Geipel (2018) offer a concept of 'The Blockchain of Circular BIM Things' facilitating the transfer of [near] live data about components in the building to the BIM model providing updates on the 'as is' state of the building, optimising performance, predicting building lifespan and potentially extending the lifespan as well as providing detailed building information at the demolition stage. The use case of integration between BIM, IoT and blockchain is proposed by Ye *et al.,* (Ye *et al.*, 2018) for creation of a DAO for building maintenance systems resulting in a wholly automated system at the operations phase.

A more disruptive effect is the possibility of actually removing intermediaries from the construction project supply chain. The economic organisation and structure of the British construction industry illustrated by Ball (2014) remains in a state where it is dominated by main contractors who are essentially intermediaries between the owner and the lower supply chain and rely on cash flow for profit. The apparent benefits of DLT may bring the demise of some industry players.

Key challenges include: the cost of implementing DLT as each building system or component would need an IoT-enabled device; developers of appropriate technology not having the construction industry in mind so a significant time lag is expected (Heiskanen, 2017); the construction industry is slow to adopt new technologies; implementation costs impacting the rate of adoption; and scant knowledge and understanding of the benefits of DLT in construction, with dissemination of that knowledge presenting further challenges (Barima, 2017).

[7] Business Models and Organisational Structures

DLT will affect business models within organisations and organisational structures will change as viable alternatives to traditional methods of practice become available. At an organisational level, DAOs will become commonplace; made possible through smart contracts. DAOs function like traditional organisations but are not owned by anyone; they are fully automated and decentralised running on a P2P network. They incorporate machine learning technology and any profit derived from a DAO is based on a stake mechanism (Zhang and Wen, 2017). They are stateless so impervious to conventional regulations and will change operations and organisation of society (Kinnaird and Geipel, 2018). Self-driving taxis will use fares they earn to pay for fuel, repairs, insurance and replacement at its end of life (Boucher *et al.*, 2017). DLT will affect value-proposition, -creation, -delivery, -capture and -communication through authentication of goods and services, disintermediation and efficiencies (Nowiński and Kozma, 2017). Financial reporting will be revolutionised as data will be readily available on the ledger negating requirements for monthly/quarterly/annual reports (Tapscott and Tapscott, 2017). Trade of goods and services will change through automated purchasing between human-to-human, human-to-DAO or DAO-to-DAO transactions removing the need for human interaction once smart contracts have been signed setting out under what circumstances they give their agreement for a trade to take place (Zhang and Wen, 2017). Trust between business parties will be redefined and DLT will support business process reengineering.

Mention was made above of the potential impact of DLT on construction industry business models. This could equally apply at the very outset of the process with the way projects are funded. Whatever the source of funding used for clients and contractors (i.e. working capital and retained profits, clearing bank and merchant bank loans, lenders' and shareholders' equity in the Private Finance Initiative and Public Private Partnerships), financial protection against loss is normally required. This is effected through a wide variety of contractual and extra-contractual measures, including retention funds, performance bonds, parent company guarantees, and collateral warranties (see Hughes et al., 1998). If, as Underwood (2016) suggests, blockchain can mitigate these risks then the need for such measures will be reduced or even removed.

Writing about the impact of technology on business-model innovation, Gambardella and McGahan (2010) observe that 'in the past, commercial opportunities or technological problems called for innovations and technological solutions; today, technological solutions are seeking commercial opportunities to trigger, or technological problems to solve'. Such a commercial opportunity is crowdfunding/crowdsourcing as a source of finance for construction. Conventional markets are composed of buyers, sellers and intermediaries. As Zamani & Giaglis (2018) point out, DLT allow the elimination of intermediaries. This, together with the vector of e-commerce creates wider, non-traditional funding opportunities such as crowdfunding. Little has been published that is specifically related to crowdfunding in the property and construction sectors, an exception being by Mercado (2017).

Roles of individuals and internal business structures will be changed by DLT. Hierarchies are likely to become much flatter as decision-making becomes autonomous based on experience and expertise reducing the level of involvement from senior management seen today (Kypriotaki *et al.*, 2015). Existing roles will be supressed whilst new roles will be created such as that of a smart contract mediator (Tapscott and Tapscott, 2017). Relaxation of centralised management could lead to fewer errors and corruption that can be seen in current systems and the introduction of more flexible and transparent democratic processes. Concerns relate to regulation of such organisations and the potential for people to set up DAOs with the purpose of perverting the law (i.e. through sale of illicit goods) or simply operating outside of current regulations (Boucher *et al.*, 2017).

The coupling of DLT and the Internet of Things (IoT) will drive digital transformation within organisations. However, lack of standards and suitably skilled IT personnel are barriers to overcome (Hossain, 2017).

3.1.2 Summation of the Systematic Literature Review

The seven categories of application of DLT in the built environment presented in this review highlight the potential impact this new form of internet can have on society as a whole. DLT focuses on returning ownership of oneself back to individuals whilst creating more democratic and transparent systems emphasising traceability and accountability. People continuously interact with the built environment which is why this review considered different facets alongside the construction industry. With a move toward a circular economy centred on waste reduction it is easy to see how the categories interact and complement one another. The fully-realised "smart" vision of the future results in complete integration of each of these aspects from smart devices in the smart home that make up smart communities that make up the smart cities currently being constructed that use smart energy and are governed by smart governments. The smart transformation results in many activities being automated. If at a point in the future automated payments are realised through smart contracts, myriad activities have the potential to be made faster, more efficient and cheaper. However, the following sub-section highlights many of the challenges offered in the literature to be overcome before acceptance of a "smart world" based on DLT can become a reality.

3.1.3 Challenges and opportunities of adoption of DLT in the construction industry

An extensive list of the challenges and opportunities related to implementation of DLT in the construction industry was compiled from the body of literature reviewed. In addition, grey literature (e.g. industry reports, agency reports, online articles, news articles, blogs) was consulted to ensure the list was as comprehensive as possible and is presented in Tables 2 and 3. It is not intended to be exhaustive. The non-construction-specific challenges and opportunities highlighted are equally applicable to the construction industry, however, specific examples were not available to provide context. In Tables 2 and 3, each challenge and opportunity has been mapped across four dimensions that were identified consistently across the literature (technical, policy, process and social) and overlaid onto the DLT Four-Dimensional Model discussed in section 4.1 below.

Table 2: *Challenges related to implementation of DLT in the construction industry*

CHALLENGE	*DESCRIPTION & CONTEXT FOR CONSTRUCTION*	*Tec*	*Pol*	*Pro*	*Soc*
Authentication of data	Ensuring data uploaded to the DLT is legitimate; could cause fraudulent activity within the supply chain (Nowiński and Kozma, 2017).	•		•	•
Bandwidth & connectivity	Sufficient server capacity required for stability of the system along with continuous internet connectivity (Bocek *et al.*, 2017; Kshetri, 2017). Elements of the supply chain delivery system could fail with lack of connectivity (Bocek *et al.*, 2017).	•			
Coding of smart contracts	Human error and badly coded contracts could be disastrous (Nehaï and Guerard, 2017). All construction projects are reliant upon well executed contracts that set out all parties' obligations thereunder (BRE Group, 2018).	•	•		
Energy consumption	Massive amounts of energy are required to run Proof-of-Work protocols (Kshetri, 2017; Nehaï and Guerard, 2017). This impacts the built environment regarding emissions, grid capacities and demand management (Nehaï and Guerard, 2017).	•	•	•	•
Exchange rate volatility	The value of Bitcoin fluctuated between $1,000 and $20,000 in 2017 (Higgins, 2017). Fluctuations in cryptocurrency valuations means they are not yet stable enough for use in construction projects (Koutsogiannis and Berntsen, 2017).		•		
Interoperability	Where different applications need to communicate, there are challenges with transfer of data. This is already seen as a key challenge to Building Information Modelling in construction (Wang *et al.*, 2017b).	•			
Legal	There is a lack of legal precedents and regulations (Winfield, 2018b). Construction relies heavily on legally binding contracts to operate and has problems with enforcing regulations (Hackitt, 2018).		•		
Malicious attacks	Different types of attacks present risks for use of DLT. Theft of data/currency pose threats to smart cities, construction projects etc. (Dorri *et al.*, 2017b).	•			
Readiness for adoption	Full adoption requires information sharing and collaboration from all participants. Some of the construction industry's biggest problems centre on sharing of information, trust and collaboration (Barima, 2017; Belle, 2017).	•		•	•
Resistance to change	Implementation requires process changes at all levels of the organisation (Zamani and Giaglis, 2018). The industry is historically resistant to change so may not realise all possible benefits of DLT (Koutsogiannis and Berntsen, 2017).			•	
Skills	Given its nascence, there is a significant lack of people sufficiently trained in DLT (Kshetri, 2017). Fresh new talent is needed in the industry for successful implementation (de Cicco, 2018).	•	•	•	

Technological state of the industry	There is an underlying requirement for a certain standard of technology to exist within an industry before implementation. The industry is not yet sufficiently digitalised to take full advantage of DLT (Koutsogiannis and Berntsen, 2017).	•		•	•

Non-construction specific challenges: poor application programming interfaces (APIs); dark net activity; data protection and 'right to be forgotten' issues with an immutable ledger; risk of tampering of smart devices; lacks flexibility and scalability as system requires consensus for changes to be made; job security at risk due to automation; nascent technology; privacy is sacrificed in place of transparency and auditability; redundancy is costly and presents issues of data storage as DLT grows in size; lack of regulation, role of state unclear, currently no authority to regulate cryptocurrencies; growth needs and means of financing scalability are unknown**;** security and confidentiality of transaction information is challenging, particularly in public blockchains**;** forks can be created as some nodes update software and others do not**;** throughput and latency of transactions is an issue where cryptocurrencies cannot compete with the likes of Visa who can process ~20,000 transactions per second.

Table 3: Opportunities related to implementation of DLT in the construction industry

OPPORTUNITY	***DESCRIPTION & CONTEXT FOR CONSTRUCTION***	***Tec***	***Pol***	***Pro***	***Soc***
Collaboration is increased	Data is more transparent so will be shared more freely increasing collaboration and trust between parties (Winfield, 2018a). Tokenisation will reward parties for data sharing (Koutsogiannis and Berntsen, 2017), reputation ratings will encourage more strategic partnerships (Belle, 2017).			•	•
Digital Twinning	A digital replica of a built asset throughout its lifecycle provides valuable information to all stakeholders (BRE Group, 2018). With IoT, drones and real-time data, DLT supports digital twinning by improving inspections (Koutsogiannis and Berntsen, 2017).	•		•	•
Disintermediation	DLT removes the need for intermediaries and guarantees execution of transactions; smart contracts automate processes and payments (Koutsogiannis and Berntsen, 2017); clients have more control over project time, cost and scope (Av, 2018).		•	•	•
Efficiencies	Promotes efficiency in international B2B trade; increases access to trade and supply chain finance (Kshetri, 2017). Automating activities allows for reallocation of resources reducing administration, transfers risk and reduces time and cost (Belle, 2017).			•	•
Faster Processes	Processes become streamlined and therefore faster. Reduces the need for multiple verifications as they can be accessed by all participants on the DLT, especially in design and planning (BRE Group, 2018).	•		•	•
Immutability	Changing already chained blocks is very difficult so the ledger is considered immutable (Kounelis *et al.*, 2017). Timestamping, smart contracts, multi-signature transactions, smart oracles create real work depositories of information (Turk and Klinc, 2017). Client (often the taxpayer) sees cost reductions (Barima, 2017).	•	•	•	•
Low Transaction Costs	Intermediary costs are eliminated; efficiency is increased in international payments; property registration costs are reduced (Kounelis *et al.*, 2017; Kshetri, 2017).			•	•
Proof-of-Ownership and Rights	Ownership, IPR and rights can be recorded for many types of assets from vehicles to buildings to bonds (Yermack, 2017) and can be made explicit for shared BIM models leading to better trust between parties (Kinnaird and Geipel, 2018).		•	•	•
Provenance	DLT and IoT-enabled devices allows for supply chain tracking of goods and services in [near] real-time (Kim and Laskowski, 2016). Procurement and supply chain activities are streamlined and allow for more robust and quicker investigations (Barima, 2017; Mathews *et al.*, 2017; Zheng *et al.*, 2017).	•	•	•	•
Reduces Human Error	Automation of tasks, use of sensors, artificial intelligence and smart contracts reduces risk of human error. Certification/verification of coding through DLT will provide quality assurance for construction projects (BRE Group, 2018).			•	•
Smart Contracts	Automatically satisfies conditions set out in the contract upon meeting pre-set obligations. Construction contracts written into code will change how organisations operate, speed up payments, reduce disputes etc. (Cardeira, 2015; Boucher *et al.*, 2017; Zheng *et al.*, 2017).			•	•
Societal Benefits	DLT will put the needs of society and challenges at the centre over technology development (Ølnes *et al.*, 2017). Can help extend asset lives through better facilities management with scheduled activities and monitoring with IoT (Belle, 2017).				•
Traceability and Auditability	Immutability adds transparency to agreements and transactions; allows for better visibility and real-time tracking of materials in projects and supply chain from provenance (Atzori, 2015).		•	•	•
Workflow Improvements	Open project environment through increased collaboration and transparency results in accountability and project control; may solve some BIM adoption issues as sharing increases (Koutsogiannis and Berntsen, 2017); workflows can be automated and made faster (Fiander-McCann, 2018).			•	•

Non-construction specific opportunities: Compensation for created value through increased control of access rights and payment structures; cross-border trade; reduces corruption through setting specific controls e.g. on how land titles can be transferred; distributed systems lead to decentralised power and more democratic systems; increases differentiation and competition through emergence of new markets; promotes inclusion bringing goods and services to people across the globe; integration of services through IoT and smart devices; Big Data sets on immutable ledgers offer better predictive capabilities; increases prosperity through granting access to the global economy through, for example, smartphones offering new lines of credit, suppliers, partners etc.; inbuilt resilience makes the system resistant to external threats and eliminates single point of failure; transparency holds people to account and reduces the ability to commit fraud; distributed systems reduce the need for trust; community-led systems result in user empowerment; move towards a value-drive society and away from price-drive economy as technology develops and focuses on individual and community needs.

3.1.4 Bibliometric indicators

International scientific influence is an important parameter when assessing the performance of research and, while the key focus should be on qualitative analysis through peer review, quantitative assessment provides support to qualitative research through the use of bibliometric indicators (van Raan, 2003, p. 20). They should be "accurate, sophisticated, up-to-date, combined with expert knowledge, and interpreted and used with care" (Moed, 2009, p. 13). Bibliometric analysis provides information on a country's research focus and makes comparisons on an international level with other research communities (Okubo, 1997). This paper uses the *number of papers* indicator focusing on the following categories: country of authors, publications per year, publication type and keywords. The data for the first three indicators were compiled directly from the papers. Data for keyword analysis was organised in EndNote and exported into BibExcel, an open source programme for analysis of bibliographic data (Persson *et al.*, 2009). Paper counts, where 'paper' referrers to any type of scientific text, allow for *relative* impact analysis of data amongst the body of knowledge that exists measuring the quantity produced based on the metric being considered (Okubo, 1997). In addition, a summary of the different DLT used across the body of research is presented.

In Figure 1, the body of knowledge was organised by country of lead author with the top contributing countries being the USA, China, Australia, the UK, Italy and South Korea.

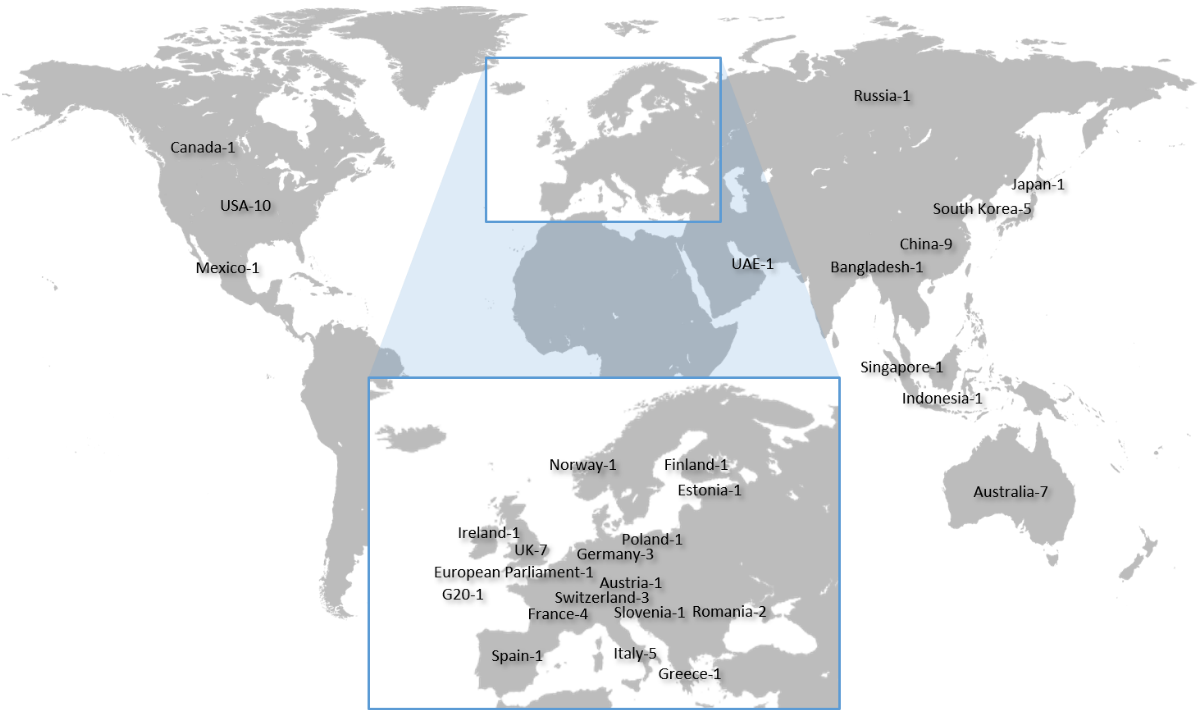

Figure 1: Distribution of papers by country of lead author

Given the infancy of DLT and the slow take-up of new technologies generally in the construction industry, the majority of papers for this study were published very recently. One paper was published in 2014, two in 2015, six in 2016, 44 in 2017 and 20 in 2018. The jump from six papers in 2016 to 44 papers in 2017 demonstrates the rapid increase in interest in DLT for applications in the built environment and it is expected that the body of knowledge will expand significantly from 2018 onwards.

Almost all the papers reviewed for this study were peer-reviewed, however, due to their relevance and contribution to the research, it included a small number of papers from grey literature (i.e. industry and government reports) and '*Other*' which included a paper from the Social Science Research Network (SSRN) repository and a book chapter. The papers consisted of 30 journal articles, 37 conference papers, four from grey literature, and two *other*.

Keyword analysis was conducted in BibExcel following instructions from Persson *et al* (2009), the results of which can be seen in Figure 2. Of the 73 papers reviewed, 13 did not include keywords. Where author keywords were not provided in the paper, where available, they were taken from the publisher's website or a database (i.e. IEEE, Compendex). Terms with the same or similar meanings were grouped together and their count cumulated to provide an accurate ranking. Keywords with one or two counts were not included in this analysis. The term "blockchain" and variations thereof had the highest number of counts followed by smart contracts, security, Internet of Things (IoT), smart city and peer-to-peer.

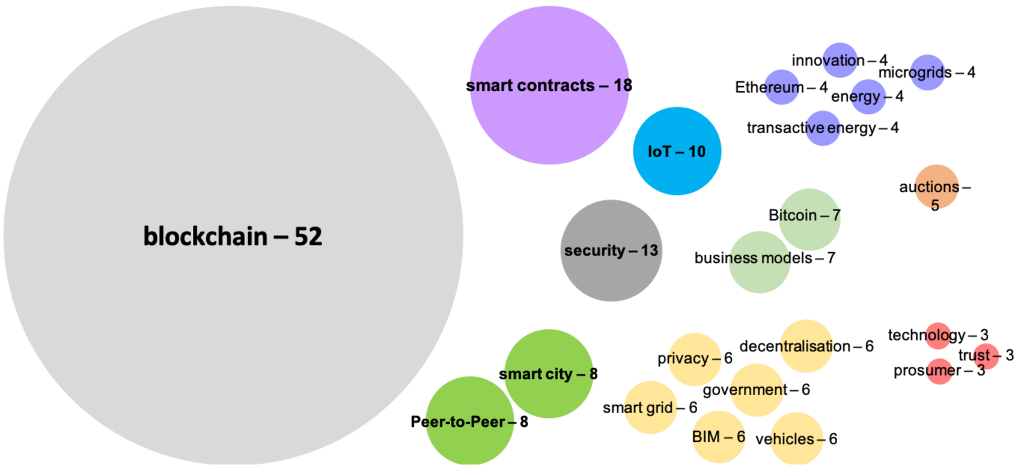

Figure 2: Analysis of top keyword counts

The final indicator used for quantitative analysis of the papers reviewed for this study is the distribution of technology employed. The Bitcoin Blockchain is the most widely used appearing in 25 papers, followed by Ethereum appearing in 14 papers. Multichain appeared twice and five papers referred to other blockchains. As a number of papers did not conduct studies or provide empirical data, there 28 papers that did not use any DLT. Additionally, one paper referred to both the Bitcoin Blockchain and Ethereum.

3.2 Focus Group Discussion

During the exploratory stages of the research, a focus group was held with eight people on the premises of a UK university. The group consisted of five academics, four with knowledge and understanding of DLT; two PhD students researching BIM and digital construction innovation; and one industry practitioner. The purpose of the focus group was to obtain views on the use of DLT in the built environment, specifically, the potential benefits and key challenges facing its implementation. The discussions that took place helped direct the development of the framework presented further on in this paper.

The one-hour session began with an informative presentation on DLT and their applications in the built environment, as identified through the systematic literature review discussed above. This was then followed by an open discussion around the benefits and challenges of DLT applications in construction.

One participant commented that blockchain in the built environment "*must be considered as a socio-technical system*" while another raised the question of whether *"it has the potential to address one of the biggest challenges in the construction industry, which is trust"*. Discussions took place around whether a decentralised system is suitable and whether projects, organisations and the industry in general would still benefit from a [more] centralised ledger. Consideration was given to DLT in practice and the frequency required for transaction processing whether it be real-time, near-real-time, hourly, weekly, monthly etc. as this would impact on the technological requirements of any system implemented. Discussions around application in the supply chain considered authenticity of data with one participant commenting that, "*Blockchain doesn't remove the fact that people can be dishonest. RFID and IoT-enabled smart dust don't guarantee that a shipment has reached its place of delivery just because the blockchain says it has when people can deliver the sensor from a shipment of bricks without the bricks and have the shipment automatically register as complete."* Finally, thought was given to the types of information to be recorded on the ledger during a construction project aside from financial transactions such as communication, asset/IP information, labour etc. and whether the '*as is'* functioning of those transactions can be improved across the industry.

3.3 Interview with senior industry representative

In April 2018, an interview was held with a senior industry representative with considerable experience in contract drafting, procurement policy and acting in an advisory capacity to several national policy and legislative groups in the UK and overseas to discuss the potential for DLT in the construction industry. The interview lasted three and a half hours and used a semi-structured approach. A structured approach would not have been appropriate given the newness of the subject area and an unstructured approach could have been too broad to ensure focus was given to the areas considered important by the interviewer or could have resulted in missing key areas of interest (Kothari, 2004). Those areas of specific interest were the potential use of DLT for Project Bank Accounts (PBAs) and the underlying challenges of the construction industry. However, the semi-structured approached allowed for emergence of regulations and compliance being discussed as one of the biggest challenges facing the construction industry.

In terms of the validity and usefulness of the interviewee's opinions, it was important that s/he was:

- an expert from within the construction industry;
- understood the key challenges facing the construction industry;
- has experience of engaging with different types of organisations across the industry from contractors at all tiers to public sector clients;
- has knowledge and understanding of the potential for DLT in the industry.

The interviewee commented that as a result of the collapse of the UKs second largest construction company, Carillion Plc., in January 2018, "*Now, in construction, there will be more visibility of supply* *chains and more regulation using the available technology to reinforce the regulatory framework from a safety point of view"*. The interviewee went on to say that, "*The biggest problem is lack of enforceability. People are not clear what they are enforcing so people can't be held to account if we don't know who did what, when"*. Talking about blockchain, it was stated that, it *"will be the facilitator of collaboration in construction,"* and, "*The value that blockchain can add is installed at the outset of the procurement process. Every time someone does something, it will be recorded on the blockchain – who, what, when, with what materials, how, who created the design, who signed off the design etc. This would give oversight of the delivery team and would give a massive boost to the regulatory system"*. The interviewee observed that, *"Current successes for blockchain applications have been seen in industries that already have integrated procurement and delivery and are already technology driven. They are more open and receptive to digital advancements. For blockchain applications to be successful in construction, first, the whole procurement and delivery processes need to be fixed"*. With regards regulation, blockchain *"gives us a way of achieving things that can't be achieved at the moment including improvements in procurement and delivery, which, at present, are very disintegrated. Use of technology to bolster regulation would ensure there were repercussions for having the blockchain as a regulatory tool that would reverberate throughout environmental standards, procurement, delivery etc. It makes it easier to enforce the delivery processes to quality and safety standards. Project Bank Accounts could be used to limit the scope of enquiry and will be complemented by regulations through traceability. Technology that forces people to account, for example, in quality factors, will change how people operate."* These comments regarding poor regulation and enforcement practices in the UK construction industry are reinforced by the Hackitt Review (Hackitt, 2018) and represents another important use case for the application of DLT in the construction industry.

3.4 Socio-technical systems

Socio-technical systems were developed in 1951 by Trist and Bamforth (1951) with a focus on the relationship between technological and social aspects in the workplace, particularly heavy industry. The original philosophy has remained the same but there has been "a gradual broadening of enquiry to advanced manufacturing technologies(…) through to office-based work and services" (Davis *et al.*, 2014, p. 172) rendering its applicability to new developments in DLT.

Technological advancements inevitably require substantial investment; for example, when updating or switching from an older system to a newer one including software tools, equipment, training, and new production processes. However, they also have the longer-term benefit of reducing production costs and increasing profit margins if adoption is properly planned and executed. The break-even point, that is, the point in time when benefits outweigh the costs, is variable and usually a key investment consideration to be addressed in the first instance (Kandt, 2018), such that what is proposed provides real solutions rather than a patch that only fixes the system temporarily.

As Baxter and Sommerville point out, "Socio-technical systems design (STSD) methods are an approach to design that considers human, social and organisational factors, as well as technical factors in the design of organisational systems" (Baxter and Sommerville, 2011, p. 4). This applies particularly when developing computer-based systems: the social and technical factors must be considered to meet the requirements of the designed system, otherwise, the system is fated to fail due to meeting technical requirements but missing social ones (Baxter and Sommerville, 2011). Three different aspects of socio-technical systems are presented by Geels (2004, p. 900) as "production, diffusion and use of technology". In the same vein as Baxter and Sommerville, Geels (2004) highlights the importance of looking at the relationships between innovation *and* users to ensure societal needs are fulfilled. At the centre of Geels' socio-technical system is regulation: an element that produces trust and intercepts with each of the three 'aspects'. Currently in the development of DLT there appears to be limited consideration of socio-technical systems as evidenced by its lack of regulation, as reported by Ammous (2016) and Kshetri (2017); this is addressed as part of the socio-technical systems approach in this paper.

4 DLT in the construction industry: an extended socio-technical framework

This section proposes a socio-technical framework for the implementation of DLT in the construction industry, based on opportunities and challenges identified in the reviewed literature and mapped across four dimensions (technical, policy, process and social) as shown in Tables 2 and 3. The socio-technical perspective was adopted because of the increasing recognition of the importance of the social element in solutions involving technological systems (Pazaitis *et al.*, 2017). However, the socio-technical stance was extended to incorporate policy and process on the basis that a new technological system is one that needs to address other elements beyond society and technology. This extended socio-technical framework has two models at its core: the **DLT Four-Dimensional Model**, and the **DLT Actors Model** which are described in the succeeding subsections. The models are intended to improve the understanding of the concepts involved when discussing DLT applications in construction. They represent flexible, adaptable and scalable knowledge constructs and foundations that can be used for various investigations related to DLT applications in construction. For example, following descriptions of the four dimensions, the DLT Four-Dimensional Model was used to analyse the challenges and opportunities facing the implementation of DLT in construction.

4.1 DLT Four-Dimensional Model

This conceptual model represents the four dimensions involved when discussing the application of DLT within the construction sector. Figure 3 provides a graphical representation of the model and its four dimensions. The model can capture potential areas of overlap among all four dimensions (i.e. the white area in the middle) and between two and/or three of the dimensions (i.e. the shaded areas surrounding the white area). This gives the model the flexibility for representing and capturing interlocking knowledge among the dimensions. This is important to preserve the endurance of the model and ensure its adaptability for different purposes, especially in a fast-evolving area of development such as DLT. The following subsections describe the four dimensions.

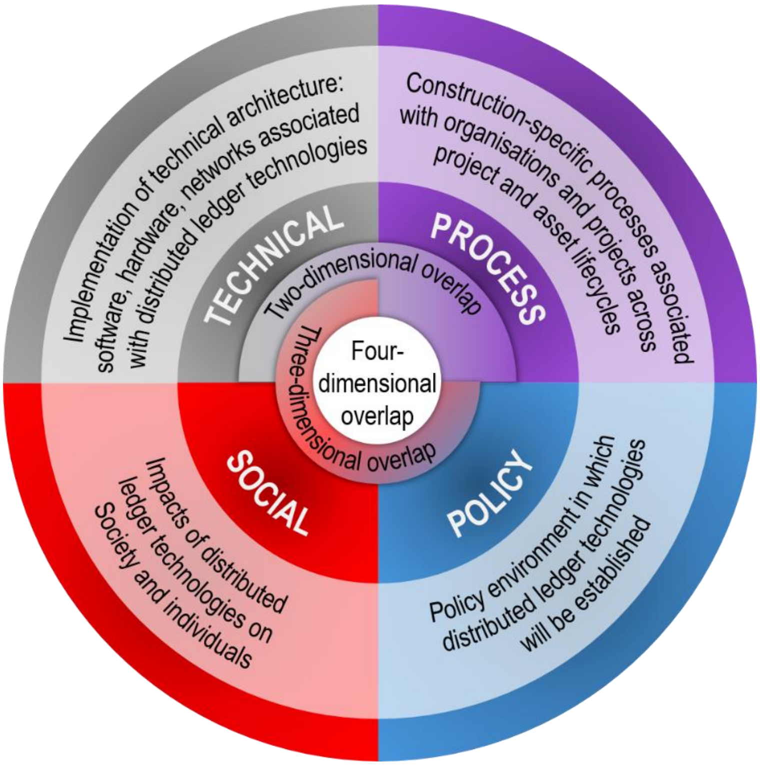

Figure 3: DLT Four-Dimensional Model

4.1.1 The Technical Dimension

The **technical** dimension deals with implementation of all aspects of the technical environment for DLT including software, hardware, networks and other infrastructure required for the system to function. Given the stage of development for DLT and the lifecycle of new technology in general, it is expected that many of the challenges highlighted above (e.g. interoperability, throughput and latency) will be solved as new products and new versions of existing technologies are released. Current offerings that are likely to have an impact on the construction industry include Ethereum (Ethereum, 2018), NEO (NEO, 2018) and Brickschain (Brickschain, 2018). A key consideration for their use in the construction industry will be whether 'unpermissioned' or 'permissioned' ledgers are required. Upon taking the decision, considerations should then turn to scalability, security and privacy, integration with hardware (e.g. sensors), integration with software (e.g. IoT, APIs, interoperability, BIM models, networks) and data frequency requirements (e.g. real-time, near-real-time, hourly, weekly, monthly).

4.1.2 The Policy Dimension

This dimension represents the **policy** environment in which DLT will be established; encompassing regulations, laws, policies, standards and compliance. At present across most countries looking to the technology these areas are either non-existent or just emerging. Examples of the latter include Russia (Georgiev, 2018) and China (Coin Idol, 2018) who have begun to establish such regulations and standards. Due to many governments having a goal of establishing smart cities, they have a responsibility to sufficiently investigate the suitability of DLT and to ensure appropriate regulatory and technological infrastructure is in place to allow it to thrive long-term facilitating its adoption and integration (e.g. with other smart technologies). The challenge will be in developing a regulatory environment that promotes integration of services, overcoming problems of interoperability and providing a manageable system without inhibiting innovation. On this basis, plans should also involve educating the general public of the benefits and operation of DLT as well as informing them of the potential security and privacy issues to enable it to be a successful user-run system based on user-generated data. Additionally, robust succession planning is essential to train sufficiently skilled people to run the system mitigating resourcing as a potential barrier to its implementation.

4.1.3 The Process Dimension

The **process** dimension considers the practicalities of implementing the technology in the construction industry and how individuals and organisations will embrace and use it. This dimension involves: (1) understanding of the implementation of DLT in procurement, design, construction, and operation and maintenance of facilities; and (2) capturing the possibilities and effects of DLT on underlying management processes of the entire project lifecycle. In particular, this dimension will prompt individuals and organisations to consider the specificities of how, when and where DLT will integrate into the project and asset lifecycles; how existing processes and procedures will change as a result of its implementation; what changes in organisational structures, business roles and business strategies (including business models) will be required to fully exploit the technology; and what needs to be done in terms of regulation at organisation, project, and supply chain levels to ensure compliance with both industry-wide regulatory frameworks and client requirements.

4.1.4 The Social Dimension

The **social** dimension is focused on the impact DLT will have on society and its integration into the real world representing the social system where the benefits will be realised. Such considerations are gaining increasing importance in the light of the increased recognition of the social impacts of technological systems: examples being the data scandal involving Cambridge Analytica (The Economist, 2018) and global policy changes such as the EU General Data Protection Regulations (GDPR). How data is generated, collected, stored and handled and what is uploaded (into any system, including a blockchain) is more important than ever, particularly with regards privacy and security. Environmental sustainability should be at the centre of technological development particularly given the high levels of energy consumption seen in distributed ledgers that use Proof-of-Work protocols. These aspects reinforce the need for DLT to be addressed as a socio-technical system as the overlap between technology and its social impacts are clearly visible. They must be considered together for any DLT application that promotes information sharing in order to avoid compromising on privacy and hindering collaboration between parties. For DLT applications in construction, the principal focus of this dimension will be at the operational phase of assets, although all other phases (e.g. design and planning, procurement, and construction) will also be relevant.

4.1.5 Mapping challenges and opportunities

To demonstrate an example of how the DLT Four-Dimensional Model can be used to improve the understanding of DLT in construction, the challenges and opportunities identified from literature in section 3.1.2 (including those non-specific to construction) have been mapped in Figures 4 and 5 across the different dimensions and their overlaps. The dotted line indicates those challenges and opportunities that overlap two dimensions that are not positioned next to each other in the model. At a later stage in the implementation process, and when used alongside the DLT Actors Model, this will assist in identifying the actors to consult when addressing a particular challenge or opportunity.

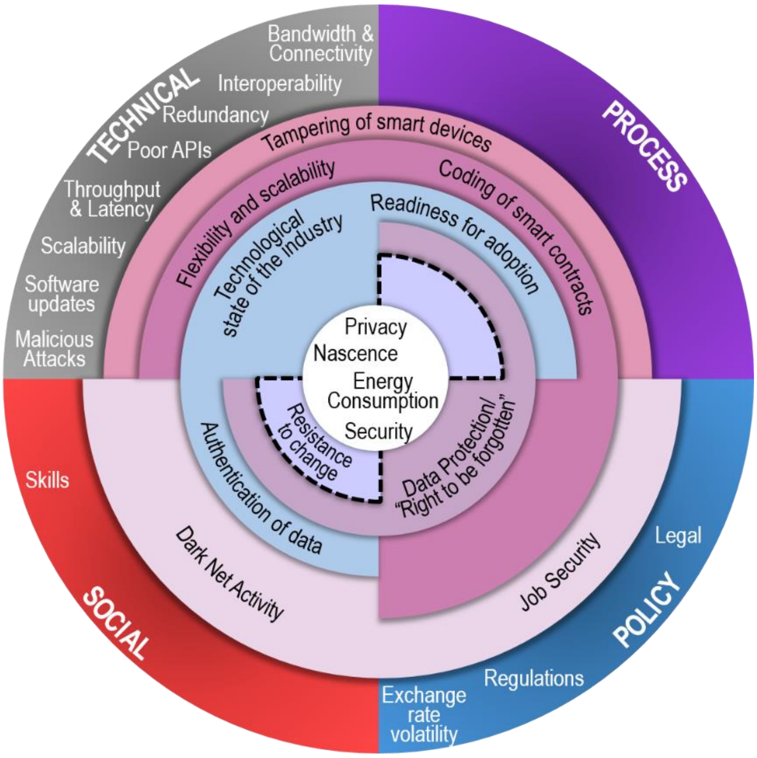

Figure 4: Challenges mapped across the DLT Four-Dimensional Model

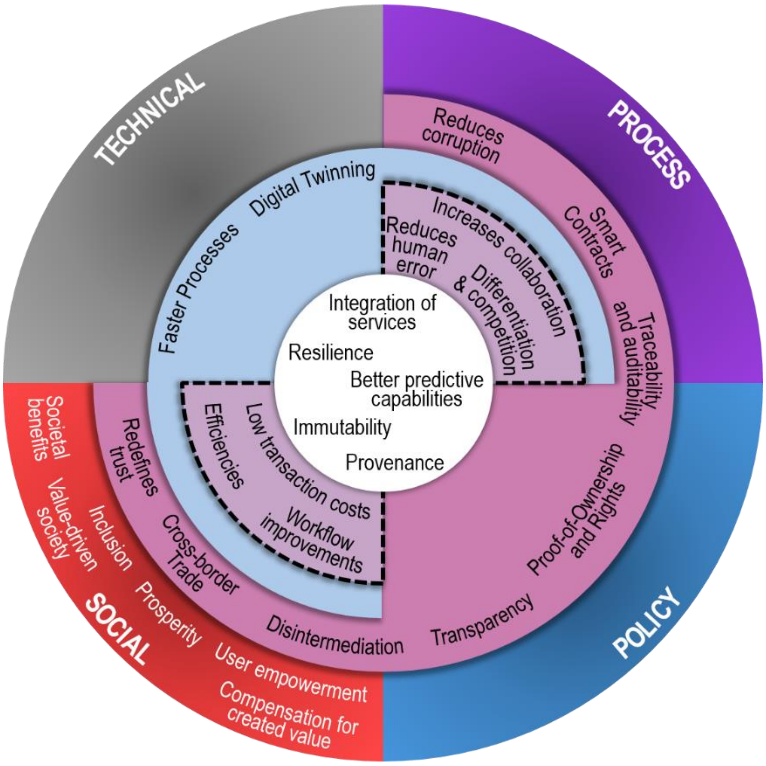

Figure 5: Opportunities mapped across the DLT Four-Dimensional Model

4.2 DLT Actors Model

This model identified the actors across each of the four dimensions representing the DLT domain in construction. Due to the complexities of new technological systems, identifying and engaging with associated actors during the development and implementation phases ensures any solution offered meets the requirements of its users and beneficiaries. Within the context of the construction industry, 16 different actors have been identified and mapped across the four dimensions in Figure 6 and described in Table 5. Each actor is made up of either individuals, groups or organisations based on their involvement with DLT. A number of actors belong to more than one dimension.

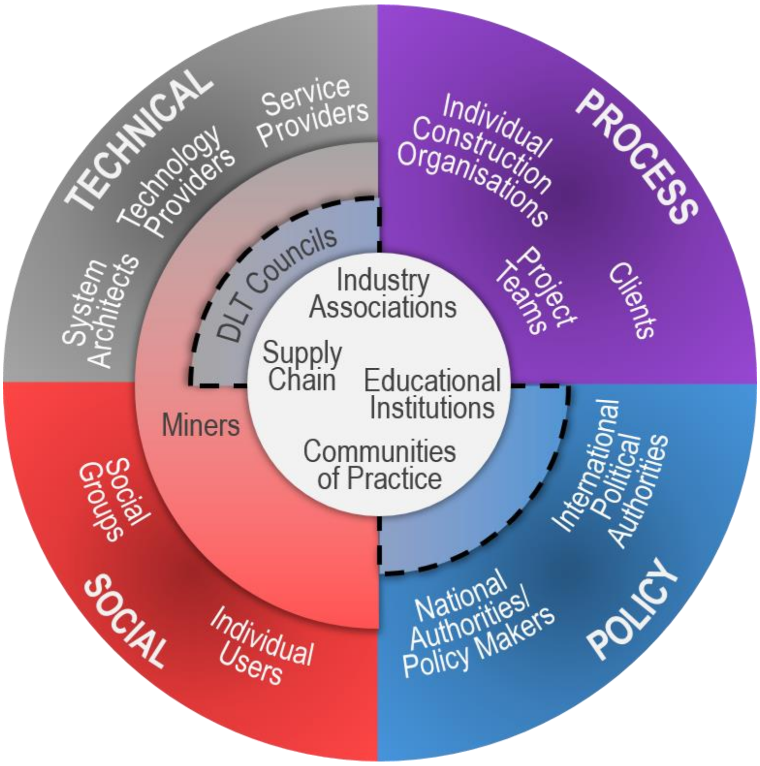

Figure 6: DLT Actors Model

This model can be used to plan the complementary effort of different actors in the adoption and diffusion of DLT for construction applications and to assign varying levels of responsibility for the actors. It can be used to assess and benchmark the level of contribution required by each actor during adoption of DLT and can support assigning of roles and responsibilities throughout the process. Actors have been allocated one of three levels of contribution: 'primary' (those actors who have a direct role in development of the technology, policies, standards, and regulations and who have a say in how technologies develop over time even after adoption); 'secondary' (those actors who will use the technology day-to-day but who do not necessarily input into its functionality); and 'supporting' (those actors who may contribute to data uploaded to the ledger or who have an interest in how they function but do not contribute to the running of the ledger nor use it for commercial purposes).

To demonstrate how the model works, three examples are given. During the early stages of DLT development, the *System Architect* has a primary role as she is the person(s) responsible for creating the distributed ledger with a particular focus on software. The type of distributed ledger required will depend on its use. Public ledgers have different requirements to private ledgers, particularly with regards security. The System Architect will be responsible for ensuring any requirements are met depending on the client and/or application. They will need to be aware of regulations to ensure that any solution is compliant. *Individual Construction Organisations* are considered to be secondary contributors. While they are most likely to use off-the-shelf technology, especially after adoption of the technology becomes more widespread and the options available more varied, in some circumstances they will be purveyors of new technological solutions dependent upon their organisation's needs. However, they will not be the direct developers of any new solution; this will be contracted out to the supply chain. *Social Groups* have been classed as a supporting contributor as they have an interest in DLT but do not necessarily have any influence over it other than their right to lobby authorities with regards how their use impacts on day-to-day lives; they will not be developing the technology nor using it on a commercial level in the context of the construction industry but will be impacted by it.

Table 4: Actors associated with DLT

Dimension	Actor	Description	Contribution
Technical	System Architects	Individuals and organisations who develop DLT including programmers, coders, software developers, system engineers etc.	Primary
	Technology Providers	Individuals and organisations who develop hardware, software, networking architecture for DLT and those associated with enabling or interrelated technologies (e.g. IoT, sensors, drone technology).	Primary
	Service Providers	Companies involved in providing a technical service to organisations using DLT, particularly where private ledgers are used.	Secondary
Political	National Authorities/ Policy Makers	State and local government authorities responsible for making policy, writing standards and setting regulations along with enforcing them.	Primary
	International Political Authorities	International groups working together to set international regulations for transactions that cross borders to promote international partnerships and to mitigate the possibility of fraud, corruption and other criminal activities.	Primary
Process	Individual Construction Organisations	Individual organisations operating in the construction industry including main architectural, engineering, contractor, sub-contractor and facilities management organisations.	Secondary
	Project Teams	Individuals across the supply chain who specifically form the project team who have access to the ledger and who have responsibility for producing information to the ledger or consuming information from the ledger.	Secondary
	Clients	Individuals or organisations, public and private, who commission construction projects with access to information on the ledger regarding their project.	Secondary
Social	Individual Users	Individuals who use DLT day-to-day either through performing transactions or by providing data to be uploaded to the ledger.	Supporting
	Social groups	Groups of individuals with an interest in the impact of DLT at a societal level (e.g. regarding energy consumption, privacy, security, creation of a value-driven economy, ensuring societal needs are being met by technological solutions).	Supporting
Technical-Political overlap	DLT Councils	Stakeholder groups of DLT tasked with approving changes to software, data in the ledger and ensuring technology and operations comply with regulations and who have the power over how DLTs function in general.	Primary
Technical-Social overlap	Miners	Individual miners, mining pools and mining organisations operating as nodes and running the peer-to-peer network with an interest in the state of the technology and the level of energy required to run the network (in the case of Proof-of-Work).	Secondary
4D overlap	Industry Associations	Professional associations who represent the interests of individuals and organisations operating in the construction industry.	Supporting
	Supply Chain	Organisations that make up the supply chain for the construction industry that are: concerned with technical elements of the system regarding tracking and updating ledgers; impacted upon regarding international politics and regulations where supply chains cross borders; have a responsibility to operate in a sustainable manner; and who must follow processes as set by industry standards and clients.	Secondary
	Educational Institutions	Universities and other educational institutions conducting research in the field and developing programmes to train and upskill people in DLT.	Secondary
	Communities of Practice	Groups of individual practitioners with an interest in a specific area of DLT (e.g. interoperability, privacy, speed).	Supporting

5 Potential use cases for DLT applications in the construction sector

A number of use cases for application of DLT to support solutions to some of the many challenges in the construction industry have been discussed in peer-reviewed academic literature and grey literature as presented in section 3. These include: the use of smart contracts to automate payments and other activities (Cardeira, 2015; Mason, 2017; Wang *et al.*, 2017b); reforming procurement practices and supply chain activities through tracking of goods and services from provenance to in-situ use (Kim and Laskowski, 2016; Geipel, 2017); integration with BIM to generate networked ledgers of engineering information (IEBC, 2018); supporting BIM through smart contracts to: launch tendering processes, archive documents, control model access and update transaction settlements (BIM World, 2017); verification of the timing and source of the addition of components to a BIM model (Geipel, 2017); automated equipment leasing using smart contracts (Wang *et al.*, 2017b); facilities management using IoT connected devices and the transactional environment of DLT to provide a live BIM model of building performance in real-time (Barima, 2017; BRE Group, 2018; Kinnaird and Geipel, 2018); maintenance and replacement insurance (IEBC, 2018); digital twinning where DLT would provide verified data of an asset to a potential buyer or provide real-time data through sensors and smart contracts (Koutsogiannis and Berntsen, 2017; BRE Group, 2018); collaboration and information sharing through changing the trust relationship using DLT (Kogure *et al.*, 2017; Mathews *et al.*, 2017); and intellectual property rights for example using DLT to prove ownership of specific BIM components (Belle, 2017; Kinnaird and Geipel, 2018). If DLT mature to a level where even some of these use cases are realised, solutions to key challenges such as poor performance, low productivity and poor payment practices will likely advance more rapidly.

Payments in construction contracts has long represented one of the biggest challenges for the industry (Latham, 1993) and DLT are a promising development in addressing it (Cardeira, 2015; Wang *et al.*, 2017b). Funds can be embedded into smart contracts with self-executing functions making automatic payments upon completion of defined obligations, thereby speeding up payments for contractors (Wang *et al.*, 2017b). Combined with cryptocurrencies, the potential for guaranteed payments increases significantly (Cardeira, 2015). Micropayments to onsite labourers are also being explored through EtchCoin where a worker could receive payment for the work completed on the same day (Evans, 2017). Automating payments and contracts through the use of smart contracts is likely to be one of the biggest impacts DLT will have on the construction industry. This, together with tackling the issue of regulation and compliance are two use cases with the potential to make massive positive changes that will reverberate across all phases of the project and asset lifecycles.

The World Economic Forum (2018) published a White Paper presenting a framework to support business executives in assessing whether a blockchain-based solution would be suitable for business needs. Peck (2017) offered a simpler decision tree asking slightly different but pertinent questions. Here, in Figure 7, the two have been amalgamated as a means of assessing whether DLT will be suitable for a series of use cases. For this study, three use cases are analysed: (1) automated Project Bank Accounts (PBAs), (2) regulation and compliance and (3) a single, shared-access BIM model. The following subsections present step-by-step application of the decision tree to assess the uses cases in terms of the suitableness of DLT. Figure 8 shows the path through the decision tree for each use case.

Figure 7: Decision Tree to assess if a distributed ledger is required

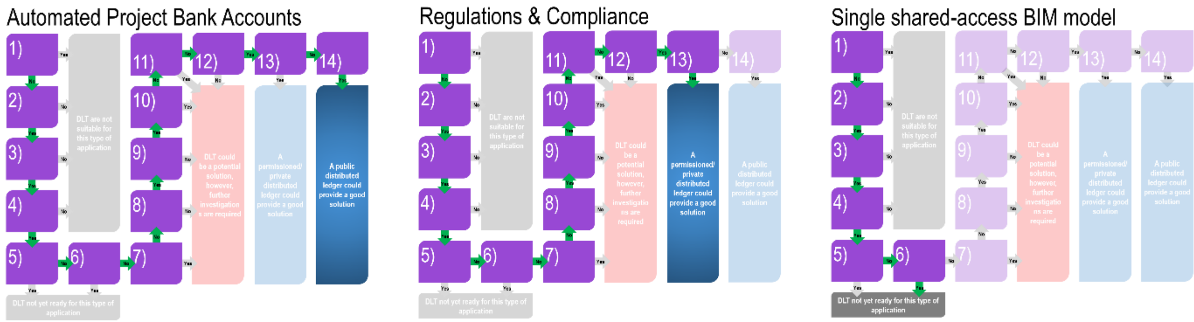

Figure 8: Path through decision tree for three construction industry use cases

5.1 Use case 1: Automated Project Bank Accounts (PBAs)

In the introduction, poor payment practices were introduced as one of the biggest challenges facing the construction industry. The extent of this can be seen through the collapse of Carillion Plc. which was the second largest construction company in the UK until January 2018 when it was forced into liquidation having been affected by problems of cashflow. According to Thomas (2018) the company had £1.5bn worth of debt and only £29m in the bank; as a result leaving thousands of individuals and organisations in a state of uncertainty, particularly as Carillion had an extended payment period of 120 days, much longer than the industry standard. An event of this magnitude has the potential to impact on the UK's economic growth (McIntyre-Kemp, 2018). It is reported that most small subcontractors may not receive any of the money they are owed, with the more fortunate ones likely to receive less than 1p for each £1 owed (Chapman, 2018).

Introduced in section 3.3, Project Bank Accounts have been offered as one solution to prevent the impacts of insolvencies, non-payments and late-payments. They were first proposed by the National Audit Office in 2005 and later endorsed by the Office of Government Commerce in 2007 (Griffiths *et al.*, 2017). A PBA is an electronic bank account that is set up by the client or the client and the main contractor to ring-fence funds for different contractors by putting the funds into a trust. Once triggered by completion of contractual obligations, payments are made by the client directly and simultaneously to members of the supply chain associated with it (Cabinet Office, 2012). As noted above, smart contracts have the ability to embed funds into a contract which will protect contractors, subcontractors and other supply chain members from insolvency (Wang *et al.*, 2017b) and could automate the (currently manually-administered) principles of payment under a PBA, increasing efficiency, decreasing payout time (Cohn *et al.*, 2017), and minimising risk of fraud, back-office costs and operational risks (Nowiński and Kozma, 2017).

The use case concerning PBAs considers the use of smart contracts to automate payments within a publicly-funded construction project. Table 5 shows the responses to the questions in the decision tree using the knowledge assimilated by the researchers during this study and related networking and interaction activities.

Table 5: Decision Tree analysis for Automated Project Bank Accounts (PBAs)

1. *Would a traditional database meet your needs?*
   No. A traditional database does not provide an immutable, historical record nor perform automated activities required with the use of PBAs in this use case.
2. *Are you trying to remove intermediaries or brokers?*
   Yes. Currently, contract payments are conducted following UK legislation that sets out how payments should be made. Payments are made by banks or financial institutions as the intermediary from the client to the main contractor and then cascaded down through the supply chain with banks carrying out the transactions. Removal of banks as the transacting institution would reduce transaction costs and increase speed of payment. However, there still needs to be a central repository where the project funds are stored like a trust until cryptocurrencies are stable enough to be used to finance projects.
3. *Are you working with digital assets (versus physical assets)?*
   Yes. As construction projects become more digital and integrate completely with technologies such as BIM and move toward digital twinning, all project-related data throughout the project and asset lifecycles will be generated and stored digitally.
4. *Can you create a permanent authoritative record of the digital asset in question?*
   Yes. This is the element that will support increased trust, collaboration and information sharing across projects through greater clarity, ownerships, rights and responsibilities.
5. *Do you require high performance rapid (~millisecond) transactions?*
   No. Construction projects do not require the level of transaction processing seen in banking and energy because financial transactions at a project level are made following UK legislation payment terms and can take months for payment transactions to actually be made due to current payment terms and the need to wait for funds to cascade the supply chain.
6. *Do you intend to store large amounts of non-transactional data as part of your solution?*
   No. For this particular use case, non-transactional data will not be required as this is focused on payment of projects contracts only. Where data are required from the project to confirm whether compliance with the project has been made, they will be stored on project servers and made accessible to those parties with access rights through, for example, the BIM Common Data Environment (CDE) rather than on the distributed ledger.
7. *Do you want/need to rely on a trusted third party (e.g. for compliance or liability reasons)?*
   No, not if the smart contract is coded correctly, transactions performed as required and a record of the transaction is uploaded to the ledger. For regulatory purposes, the ledger will provide the immutable historical record to demonstrate compliance and the smart contract will only execute upon meeting the required obligations set within it. Any smart contract will be required to comply with any industry and financial regulations from the outset.

8. *Are you managing contractual relationships or value exchange?*
   Yes. All construction projects involve contracts, often complex, between two or more parties throughout the life of the project and asset. Payments are the most important element of the contract to the contractors and represents the tangible value to be exchanged between parties.
9. *Do you require shared write access?*
   Yes. The client, main contractor and subcontractors need to be able to administer the PBA with regards payment notices and other data and transactions required to comply with the smart contract terms for a payment to be made.
10. *Do contributors know and trust each other?*
    No. The parties may know each other from previous projects, but the construction industry is notorious for lack of trust between contracting parties which is why traditional contracts have become so complex.
11. *Are contributors' interests unified or well-aligned?*
    No. Often, main contractors will attempt to pay less than was originally set out in the contract based on work performed that often results in legal disputes being raised. Therefore, with regards payments, their interests are not aligned.
12. *Is this database likely to be attacked or censored? Do you need redundant copies in multiple distributed computers?*
    Yes, in principle. Dependent upon the project, there is potential for attack or censorship. For example, public defence projects may be attacked in a bid to obtain sensitive information not in the public domain. With regards the need for redundant copies, this would protect integrity of the data as any changes would be immediately visible. In addition, project participants would be more comfortable with their own copies of the ledger.
13. *Do you need to be able to control functionality?*
    Yes. The ability to change permissions and/or add amendments to contracts regarding payment terms within the ledger may be required as contracts evolve when project schedules progress.
14. *Should transactions be public?*
    Yes, in principle. As this is a publicly funded project, there is a strong argument that the financial transactions within the contract should be made public. However, this type of information is also considered commercially sensitive so whether transactions are made public or only certain transactions are made public would need to be considered on a project by project basis.

The outcome of this analysis demonstrates that PBAs could benefit from DLT in the form of smart contracts. This particular use case contemplated the use of a public ledger. However, a private ledger could be substituted depending on the circumstances of the project. The very transactional nature of this use case lends itself to being automated; reflecting the original purpose for which DLT was developed (i.e. Bitcoin transactions). The use of DLT does not entirely remove the potential for payment disputes on construction projects, but, as argued by Margie (2017) it could, by alleviating concerns over payment, substantially reduce them thereby increasing collaboration between project participants.

5.2 Use case 2: Regulation and Compliance

The serious shortcomings of regulation and compliance were highlighted in the introduction with reference to the Grenfell Tower fire and subsequent Hackitt report and the fact that Carillion's collapse is able to happen. Table 6 presents hypothetical responses in relation to a use case considering the use of an immutable distributed ledger to record data during a project creating a historical record to demonstrate compliance with regulations.

Table 6: Decision Tree analysis for regulation and compliance

1. *Would a traditional database meet your needs?*
   No. There is a requirement for an immutable, historical ledger to allow for effective investigations following events such as Grenfell Tower and to provide proof of certifications and verifications that take place throughout the project and asset lifecycles.
2. *Are you trying to remove intermediaries?*
   Yes. The current regulatory system and enforcement of that system is not functioning sufficiently. Information is not readily available and that which is, is not comprehensive enough to demonstrate or assess compliance without extensive investigations, as shown by the Grenfell Tower tragedy in June 2017. Removal of intermediaries will make the system smoother and more robust if elements of the system can be automated and full historic ledgers of data transactions recorded.

3. *Are you working with digital assets (versus physical assets)?*
   Yes. All data from a construction project, if not already, can be digitised.
4. *Can you create a permanent authoritative record of the digital asset in question?*
   Yes.
5. *Do you require high performance rapid (~millisecond) transactions?*
   No.
6. *Do you intend to store large amounts of non-transactional data as part of your solution?*
   No. However, signposts to the correct information must be made available on the ledger to be able to demonstrate that a project complies with regulations and the location of the signposted documents must be made available on a permanent basis.
7. *Do you want/need to rely on a trusted third party (e.g. for compliance or liability reasons)?*
   Guidance from the World Economic Forum's decision tree is such that, "*If an industry has specific requirements on the use of intermediaries or trusted partners, then it may be complicated to deploy blockchain, even if other benefits of its use are readily apparent. In use cases where regulation plays a big role, it may be necessary to include regulators in the project and deliver means by which the regulators can ensure compliance with laws, such as antitrust and environmental law. This engagement will be a critical piece that needs to be addressed in many industries. An example is an industry that has strict requirements from multiple regulators, such as antitrust and environmental, each of which requires visibility into a different aspect of the transaction data, and where the issuer does not seek to display the entirety of the transaction data to any one regulator for legal or other reasons. It could be quite difficult to deploy a blockchain for this situation without regulatory engagement*" (World Economic Forum, 2018, p. 7). Therefore, to exploit DLT for regulatory compliance purposes, actors (as identified in the DLT Actors model) should collaborate on developing an approach – within the context of the extended socio-technical framework – that enables the involvement of regulators in the project to ensure compliance.
8. *Are you managing contractual relationships or value exchange?*
   Yes.
9. *Do you require shared write access?*
   Yes. All members of the project team need to have write access to the ledger to be able to update project progress and for functioning of the smart contracts within the project.
10. *Do contributors know and trust each other?*
    No.
11. *Are contributors' interests unified or well-aligned?*
    No.
12. *Is this database likely to be attacked or censored? Do you need redundant copies in multiple distributed computers?*
    Yes. Multiple copies would hold individuals and organisations to account.
13. *Do you need to be able to control functionality?*
    Yes. A private permissioned ledger will most likely be the preferred choice for publicly funded construction projects.
14. *Should transactions be public?*
    No, in principle. As with the previous use case, this will be dependent on the project as it is publicly funded. But, transaction data are most likely not required to be public due to security or commercial sensitivity reasons.

The Regulations and Compliance use case (2) is much more strategic in nature than its predecessor (Automated PBAs). The key finding from analysing this use case is the need for regulatory reform before any new solutions can be implemented. DLT can be *part of* a solution but they are not *the* solution to the entirety of the challenges faced. In question 7 of Table 6, guidance from the World Economic Forum suggests that regulators become part of the project delivery team. If this were to be the case for a construction project, they would no longer be considered a third party but rather a project participant. Under these circumstances, a DLT could prove to be an effective element in regulation and compliance of construction projects and in this instance, a public or a private ledger would be suitable depending on the circumstances.

5.3 Use Case 3: Single Shared-Access BIM Model

It was noted earlier (in Section 3.1.1) that the benefits of combining BIM with DLT are only likely to be fully realised with more interconnected and networked collaborative BIM ways of working such as those envisioned for Level 3 BIM maturity. Level 3 BIM presupposes a single shared-access BIM Model where all project participants work from one centrally held model managed by a collaborative Model Server during a construction project from the design and planning phase, through construction, into asset operation and through to the end of its life. This use case considers the use of DLT as a vector for participants' inputs/output of information into/from the model where all participants are granted access based on their rights and responsibilities throughout the project. As participants add to and update the BIM model, the ledger will automatically update each participant's version of the model across the distributed network to ensure that all participants are working from the same model in real time. This promotes collaboration and information sharing, addresses problems of trust within construction projects and encourages further uptake of BIM. Although the capabilities described are in part fulfilled by the Common Data Environment (CDE), what DLT offers to this use case is the ability to automatically and conclusively validate and verify who did the updates, what was done, how it was done and when it was done. In addition, this helps to satisfy the Hackitt Report's recommendation for a digital record (Hackitt, 2018). Table 7 shows the hypothetical responses to the questions in the Decision Tree.

Table 7: Decision Tree analysis for Single Shared-Access BIM Model for whole asset lifecycle uses

1.	*Would a traditional database meet your needs?* No. BIM Models are too complex to be satisfied by a traditional database.
2.	*Are you trying to remove intermediaries?* Yes, to some extent. The current model for delivering projects in construction includes many intermediaries for things like insurance, certifications, validations, supply chain activities, procurement, financial transactions, contract writing etc. that carry high associated costs. Removal of intermediaries will dramatically reduce project costs.
3.	*Are you working with digital assets (versus physical assets)?* Yes. Most data from a construction project, if not already, can be digitised.
4.	*Can you create a permanent authoritative record of the digital asset in question?* Yes.
5.	*Do you require high performance rapid (~millisecond) transactions?* No.
6.	*Do you intend to store large amounts of non-transactional data as part of your solution?* Yes. Ultimately, the vision would be to have an entire BIM Model on a distributed ledger for whole asset lifecycle use including: e.g. records every transaction that takes place; stores every document related to the project and built asset; automates facilities management activities; manages buildings like a Distributed Autonomous Organisation (DAO) through the use of smart contracts connected with the IoT, sensors and drone technologies; etc..

The prospect of single shared-access BIM models (as described in Table 7 and envisaged at Level 3 BIM implementation target) becoming standard practice in construction is a distant one (Kinnaird and Geipel, 2018), and one that requires considerable change to current standard workflows and business models. Until these changes occur, it is unlikely that the benefits of incorporating DLT with BIM will be realisable, though in the future they are likely. Moreover, the use case above assumed that the actual content of the BIM is uploaded into the ledger. The 'unchained' scenario, where the BIM files are stored into a management server and only their fingerprints and metadata are stored into the ledger, still represent a feasible option (Turk and Klinc, 2017) and its testing against the decision tree would have followed the same path as Use Case 2.

5.4 Evaluation of the Decision Tree

Three use cases were employed to evaluate the effectiveness of the proposed decision tree. These procedures have demonstrated the initial level of evaluation that should take place to allow a decision to be made on whether a specific use case warrants further investigations into the value of DLT. The decision tree captures the key elements of DLT and can be applied to a range of applications. In addition, it can support identification of use cases that may benefit from DLT but also recognises that DLT are still in development and do not yet provide universal solutions. Consideration should be given to the fact that just because DLT can provide a solution to construction industry challenges, it is not necessarily the best or most efficient option; all other options should be explored when considering routes to technological advancement.

6 Conclusions and future work

This paper contributes to knowledge in the following ways:

a) identifies the key areas of research interest of DLT in the built environment through categorising and analysing results from a state-of-the-art and literature review highlighting seven categories of: smart energy, smart cities and the sharing economy, smart government, smart homes, intelligent transport, Building Information Modelling (BIM) and construction management, and business models and organisational structures;

b) presents an extensive list of challenges and opportunities of DLT with specific examples for the construction industry along with results from a focus group and expert interview to demonstrate current thinking on the topic.

c) assimilates those results into developing a framework that contains two multi-dimensional conceptual models to form the basis of a roadmap for implementation of DLT in the construction sector. The DLT Four-Dimensional Model incorporates four elements (technical, policy, process and social) and the DLT Actors Model identifies a list of actors within and across each of the dimensions, which should be considered when developing any DLT-based solution for the construction industry ensuring that any solution provides benefits for society rather than just providing a technological solution; and

d) proposes a decision tool for use by practitioners to help evaluate different use case scenarios for their suitability and potential for benefitting from DLT implementation.

The biggest challenges causing slow technological adoption in the construction industry have been identified as: lack of collaboration and information sharing; poor levels of trust between parties; low productivity; late payments; lack of enforcement of regulations; and issues surrounding ownership and intellectual property rights. Three use cases (automated Project Bank Accounts; regulation and compliance; and a single shared-access BIM model) centred around these key challenges were selected and tested using the decision support tool. The results show that the first two use cases did warrant further investigations, however, the technologies are insufficiently developed for the third use case at this time.

The characteristics of DLT, namely, immutability, traceability and transparency resulting in better accountability, auditability and reduced bureaucracy, have the potential to reform practices within the construction industry to support its technological advancements and bring it in line with other industries such as automotive, mechanical engineering and logistics. This will allow the industry to better manage resources and reduce costs, project durations and payment disputes. As DLT develop and mature, many of the challenges identified will be addressed and opportunities to exploit its benefits will increase. However, the construction industry must be open to change and embrace the possibilities that DLT can bring to it if it is to overcome the problems that beset it. However, it must realise that DLT are not a solution in and of themselves but they should be accompanied with developments across the legal, social and process dimensions, as described in the proposed framework. Only in such a way, the construction sector may keep the pace with the on-going applications of DLT and other digital developments in the wider built environment on the ever-fast evolving journey towards “smart” vision of the future. In line with this need, the authors intend to further develop the framework by adopting metrics to assess the readiness levels of the construction industry to implement DLT across a variety of use cases. This will permit gap analysis of the four dimensions comparing required levels against current levels of readiness which will in turn to support recommendations for the achievement of suitable levels in the industry.

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